

Quark-Gluon Plasma: Present and Future

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We review a sample of the experimental results from AGS to SPS and RHIC and their interpretations towards understanding of the Quark-Gluon Plasma. We discuss extrapolations of these results to the upcoming LHC experiments. Finally, we present the plans to probe the QCD critical point with an energy scan at RHIC and FAIR facilities.

Introduction

It is about thirty years since the intense study of hot and dense nuclear matter in the form of Quark-Gluon Plasma (QGP) has started. A tremendous amount of effort has gone in for the development of four generations of experiments and a large number of data have been collected and analyzed. Major theoretical developments have been made at the fundamental level and theoretical models have been developed in order to understand the implications of the data. A glimpse of ongoing activities may be found in [1]. It is appropriate at this time to ask: (i) what were the expectations in the beginning? (ii) What have we learned so far? (iii) What are the prospects for the future?

Based on the two most novel properties of QCD, *viz.* asymptotic freedom of quarks and quark confinement, it was conjectured that it would be worthwhile to explore these phenomena by creating high energy and high density matter over a large volume. At these high temperatures and densities normal nuclear matter is expected to undergo a phase transition to a new state of matter, called the Quark-Gluon plasma. Interesting connections were made to the big bang model of the early stages of our Universe where a QGP state might have existed. Intense experimental programs with collisions of nuclei at relativistic

energies have started to recreate these conditions in the laboratory.

The quest for the search and study of QGP started in early eighties with the acceleration of Au beam at 1 GeV/A at the Bevalac. The early success of the experiments in terms of bringing out the collective nature of the matter produced prompted the scientists at Brookhaven National Laboratory (BNL) and CERN to make concrete programs for the future accelerator developments for heavy ions. The next milestone came with the acceleration of Au beam at 11.7 GeV/A at the AGS at BNL and Pb beam at 158 GeV/A at the CERN-SPS. First hints of the formation of a new state of matter has been obtained from the SPS data in terms of global observables, event-by-event fluctuations, direct photons, di-leptons and most importantly, the J/ψ suppression. The Relativistic Heavy Ion Collider (RHIC) started becoming operational in the year 2000 with Au-Au collisions at $\sqrt{s_{NN}} = 130$ GeV and soon after to top Au-Au energies of $\sqrt{s_{NN}} = 200$ GeV. The experimental program at RHIC included four experiments, two large and two small with the involvement of more than 1200 physicists. At present, the RHIC experiments bring out highest quality data from p-p, Cu-Cu and Au-Au at various energies. Strong evidence for the production of extreme hot and dense matter has been seen. The matter formed at RHIC has been termed as sQGP (strongly coupled QGP). The RHIC results, in combination with the ones from AGS and SPS, have enhanced our understandings of the QCD matter at different temperatures and densities.

The CERN large hadron collider (LHC) is

*Dedicated to the memory of Prof. Aswini Kumar Rath who was the Local Convenor of the DAE Symposium on Nuclear Physics (December 2007) at Sambalpur University where the talk was presented.

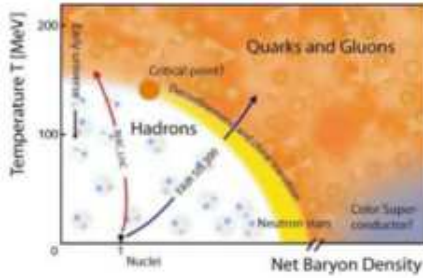


FIG. 1: Phase diagram of nuclear matter.

expected to be commissioned within one year. Heavy-ion physics is an integral part of the baseline program of the LHC which will accelerate Pb-Pb beams at $\sqrt{s_{NN}} = 5.5$ TeV, a factor 27 higher than the top RHIC energy. This increase is even larger than the factor 10 in going from the CERN-SPS to RHIC. It will lead to significant extension of the kinematic range in transverse momentum (p_T) and in Bjorken x . LHC will turn out to be a discovery machine for various types of physics and will explore QCD phenomena in great detail.

The QCD phase diagram, as shown in Figure 1, characterized by the temperature (T) and the baryon chemical potential μ_B , signifies the separation of QGP to hadronic phase. One of the major predictions of QCD in extreme conditions of high temperature or large baryon number density is the existence of a critical point at a particular temperature and density where a sharp transition between the QGP phase and the hadronic phase first appears. It may be possible to access the critical point experimentally by scanning the QCD phase diagram in terms of T and μ_B . This can be accomplished by varying beam energies from about $\sqrt{s_{NN}}=5$ GeV to 100 GeV. Such a program has recently been undertaken at RHIC[2]. Experiments at GSI[3] are planned to study this as well. The discovery of the critical point would be very important to the QGP study.

In this review, we present selected experimental results from AGS to SPS to RHIC and

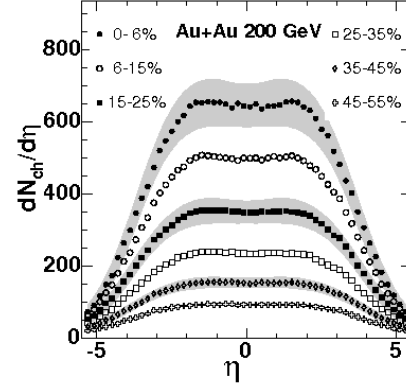


FIG. 2: Charged particle multiplicity density at RHIC energy for different collision centralities [4].

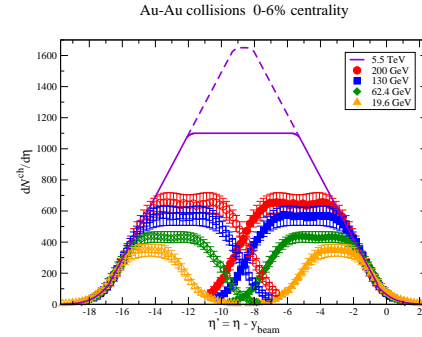


FIG. 3: Charged particle multiplicity density scaled by their beam rapidities and extrapolation to LHC energies [5].

predictions for the LHC. At the end we will return back to the questions of where we are and what to expect next.

Global observables

The comprehensive study of particle production, rapidity distributions, particle ratios, momentum spectra, flow and source size estimations provide valuable information for thermal and chemical analysis of the freeze-out conditions. One of the first results which came out from RHIC is shown in Figure 2 in terms charged particle multiplicity density for Au-Au collisions at different collision centralities [4]. Combining all the data from SPS

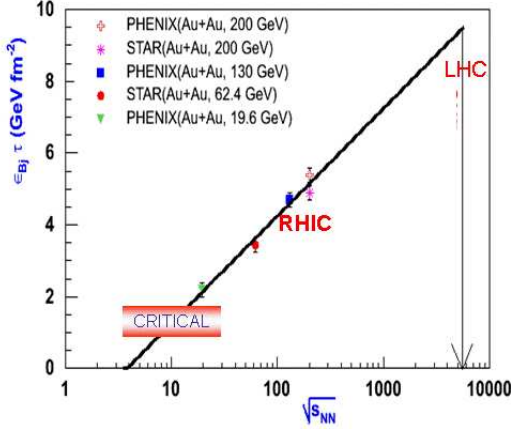


FIG. 4: Energy density as a function of beam energy. The figure indicates the possible location of the critical point and extrapolation to the LHC energy.

to RHIC, one can make an extrapolation to LHC [5] as shown in Figure 3. These data are plotted in the rest frame of one of the colliding nuclei (full symbols) and mirrored at LHC mid-rapidity (open symbols). At LHC energies, a pseudorapidity density close to 1100 at the mid rapidity is obtained. Other estimations for LHC energies give numbers between 1200-2500 for pseudorapidity density at mid rapidity [5].

Energy density estimations have been made using the rapidity densities and mean transverse momenta. The values for RHIC energies are shown in Figure 4 and extrapolated to LHC energy [6]. The energy density where the critical point occurs is shown in this figure. The energy density achieved at RHIC energies are already seen to be beyond the critical density for QGP formation.

The measured net proton rapidity density distributions for AGS, SPS, RHIC energies [7] are shown in Figure 5 with extrapolations to LHC energies. The figure shows that a complete transparency can be expected at LHC energies for a large rapidity range.

From the measured spectra and particle ratios, it is possible to estimate the freeze-out temperature and chemical potential by us-

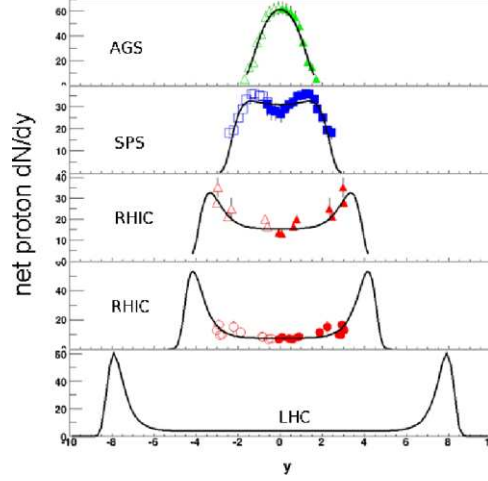


FIG. 5: Net proton rapidity distributions at various collision energies.

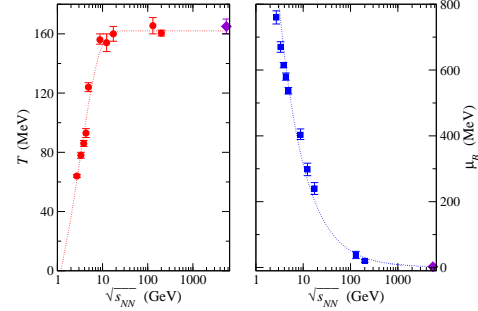


FIG. 6: Estimation of freeze-out temperature and chemical potential from thermal model fits as a function of centre-of-mass energy of the collision [5].

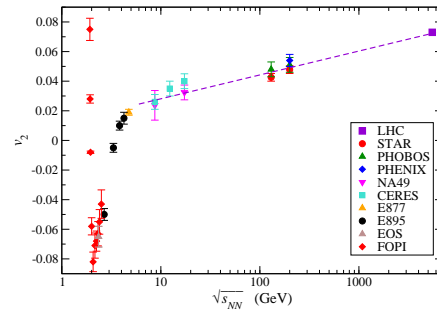


FIG. 7: Elliptic flow, v_2 as a function of centre-of-mass energy of the collision [5] for existing data and extrapolated to LHC.

ing thermal model fits [5]. This is shown in Figure 6 which can be used to map the QCD phase space. The chemical potential at top RHIC energies is between 20-40MeV and at LHC energies it is expected to be less than 10MeV. Since various lattice calculations give different values of chemical potentials (180MeV to 500MeV) for the critical point, it is obvious that a thorough energy scan is needed from $\sqrt{s_{NN}}=5\text{GeV}$ to 100GeV, in order to probe the region around the critical point.

An important measure of the collective dynamics of heavy-ion collisions is the elliptic flow (v_2). Figure 7 shows excitation function of v_2 for mid-central collisions. Because of the large values of v_2 at RHIC energies, in agreement with the value for an ideal fluid, the formation of a perfect liquid is ascertained at RHIC energies.

The dynamical evolution of the collision fireball and its space-time structure has been traditionally studied using two-particle (HBT) correlations. The multiplicity and transverse momentum dependence of three-dimensional pion interferometric radii in Au-Au and Cu-Cu collisions at different RHIC energies [8] have been shown in Figure 8. The freeze-out volume estimates with charged pions measured from such studies, show linear dependence as a function of charge particle multiplicity indicating consistent behaviors with a universal mean-free-path at freeze-out. The HBT correlations of photons is expected to provide better insight into the nature of the evolving system [9, 10, 11]. The HBT correlation studies can be studied in more detail at the LHC. Moreover, it may be possible to extract HBT radii on an event by event basis at the LHC energies.

Event-by-event Fluctuation

Fluctuations of thermodynamic quantities provide an unique framework for studying the nature of the phase transition and provide direct insight into the properties of the system created [12]. Large fluctuations in energy density due to droplet formation are expected if the phase transition is of first order and a sec-

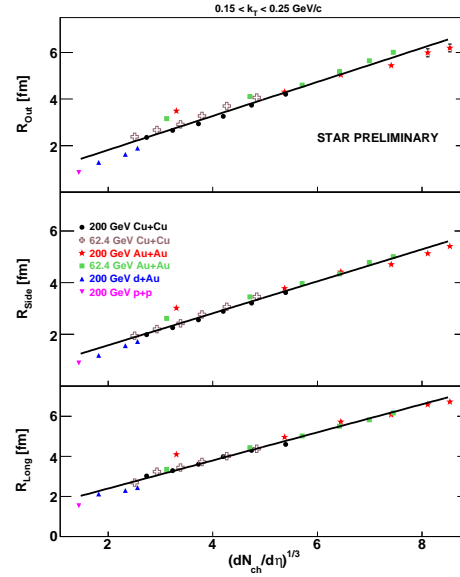


FIG. 8: Pion source radii dependence on charged particle multiplicity. The lines are plotted to guide the eye and represent linear fits to the data.

ond order phase transition might lead to divergence in specific heat and increase in the fluctuations. Fluctuations are also predicted to be largely enhanced near the critical point. Fluctuations have normally been studied in terms of $\langle p_T \rangle$ and temperature, multiplicity, strangeness, net-charge, balance functions, azimuthal anisotropy and source sizes. The formation of disoriented chiral condensates is expected to lead to large charged-neutral fluctuations.

Relative production of different particle species produced in the hot and dense matter might get affected when the system goes through a phase transition. Large broadening in the ratio of kaons to pions has long been predicted because of the differences in free enthalpy of the hadronic and QGP phase. This could be probed through the fluctuation in the K/π ratio. The dynamic fluctuation, σ_{dyn} , in the K/π ratio (Figure 9) is seen to decrease with beam energy in going from AGS to SPS energies and then remain constant.

In order to be more sensitive to the ori-

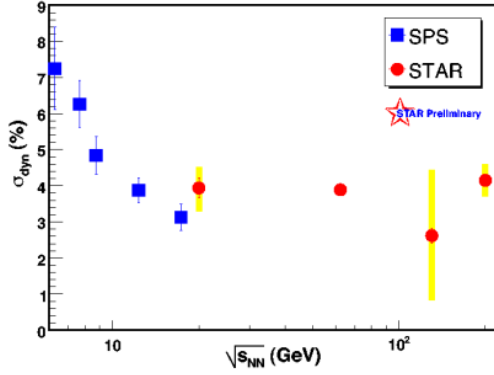


FIG. 9: Excitation function for σ_{dyn} of $[K^+ + K^-]/[\pi^+ + \pi^-]$ ratio at the SPS (left panel) and with an extension to RHIC (right panel) [13]

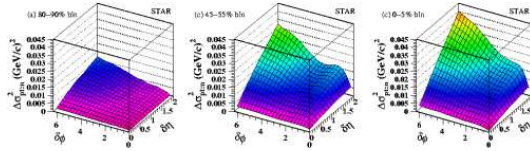


FIG. 10: Scale dependence of $\langle p_T \rangle$ fluctuation within the STAR acceptance expressed in terms of per-particle variance difference [14]. Results are given for three collision centralities (from peripheral to central in going from left to right).

gin of fluctuations, differential measures have been adopted where the analysis is performed at different scales (varying bins in η and ϕ). The scale dependence of $\langle p_T \rangle$ fluctuation for three centralities in Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV [14] is shown in Figure 10. The extracted auto correlations are seen to vary rapidly with collision centrality, suggesting that fragmentation is strongly modified by a dissipative medium in more central collisions relative to peripheral collisions. Further studies for different charge combinations will provide more detailed information.

High p_T and jets

Properties of the hot and dense medium produced in nucleus-nucleus collisions can be studied via the energy loss experienced by fast

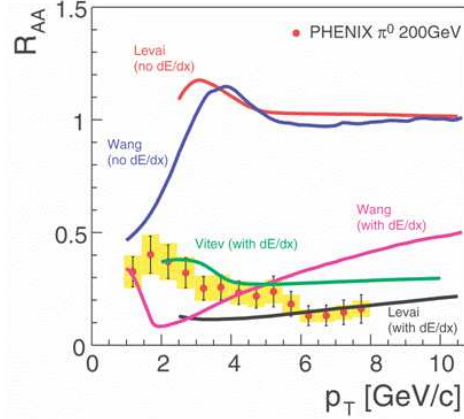


FIG. 11: The nuclear modification factor R_{AA} for π^0 compared to different model predictions for neutral pions [15].

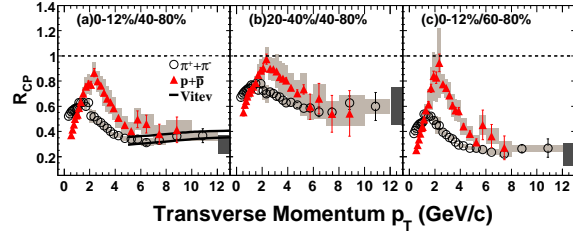


FIG. 12: The nuclear modification factor R_{CP} for identified charged pions and protons [16].

partons in the medium. Detailed measurements have been performed by experiments at RHIC for the nuclear modification factor, R_{AA} , defined as,

$$R_{AA} = \frac{dN_{Au+Au}}{\langle T_{AA} \rangle d\sigma_{p+p}},$$

for neutral and identified particles. Figures 11 and 12 give R_{AA} and R_{CP} (defined as ratio of central to peripheral collisions) as function of p_T as measured by the PHENIX [15] and STAR experiments [16], respectively. Strong suppressions are seen in central Au-Au collisions corresponding to the p-p. The results indicate that at low p_T , protons and anti-

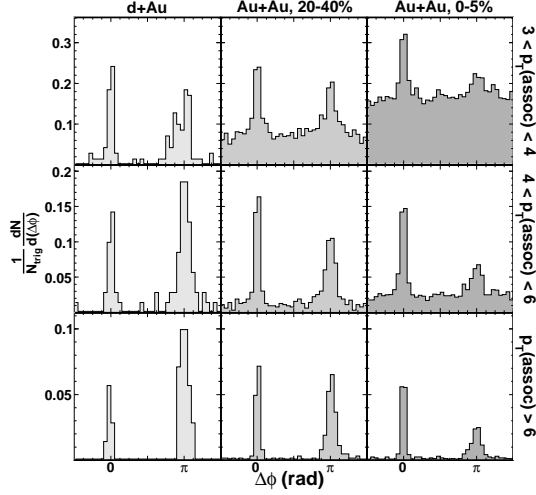


FIG. 13: Azimuthal correlation of high p_T charged hadrons. [17].

protons are less suppressed than charged pions whereas at high p_T the partonic sources of pions and protons have similar energy loss when traversing the nuclear medium. More detailed results may be found in [15] and [16].

The back-to-back correlation strength of high p_T hadrons is seen to be sensitive to the in-medium path length of the parton. The study by the STAR experiment over a broad range in transverse momenta [17] is shown in Figure 13 for d-Au and Au-Au collision at two different centralities. Whereas there is no significant change in the near side peak with the increase of p_T of the associated particles, the away-side correlation strength decreases from d-Au to central Au-Au collisions. The strongest modifications of the correlated yields are seen at lower associated p_T . More detailed measurements of nuclear modification factors and azimuthal asymmetries should be made in order to constrain the theoretical models.

The measurement of γ -jet events provides an unique probe of parton energy loss [18]. These studies are being actively pursued by RHIC experiments [19].

Electromagnetic probes and quarkonia

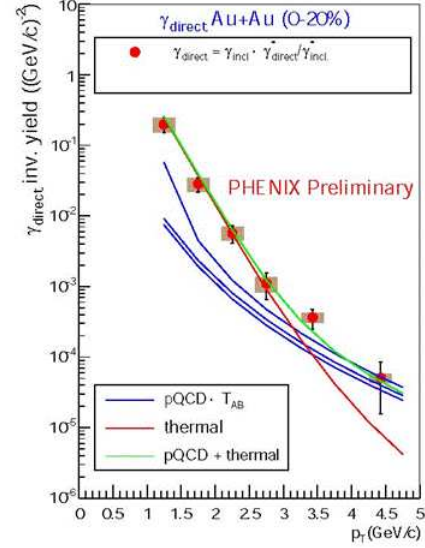


FIG. 14: Yield of direct photons as a function of p_T for central Au-Au collisions compared to various theoretical models.

Electromagnetic probes, viz., photons and dileptons have long been recognized as the most direct probes of the collision system. Owing to the nature of the interaction they undergo minimal scatterings and are by far the best markers of the entire space-time evolution of the collision. The single photon data obtained from Pb-Pb collisions at CERN-SPS by the WA98 Collaboration have been the focus of considerable interest [20]. The direct photon spectra at low p_T from the PHENIX experiment [21] is shown in 14. The yield is consistent with rates calculated with thermal photon emission taken into account.

The dielectron spectra have been measured by the PHENIX experiment [22]. This is shown in Figure 15 after background subtraction for Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV together with cocktail hadron decay sources and a pythia calculation of charm decays. The data are in good agreement with the cocktail over the full mass range. Improvement in the data quality with respect to the combinatorial background and better theoretical calculations are needed in order to make any con-

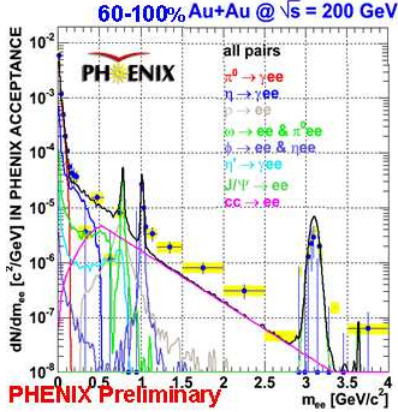


FIG. 15: The dielectron spectra Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV together with cocktail hadron decay sources and a pythia calculation of charm decays [22]

clusive statement.

J/Ψ suppression is considered to be one of the most direct signatures of QGP formation [23]. The observed suppression of J/Ψ in Pb-Pb collisions at the SPS energies [24] was considered to be a direct observation of deconfined matter. However the above statement has been contrasted by several theoretical calculations. Recent high accuracy measurement by the NA60 collaboration for In-In collisions shows that a suppression is also present in these collisions [25]. In the meantime new results from the PHENIX experiment [26] have been compared to NA50 results which show reasonably good agreement. Higher statistics data from PHENIX and STAR are necessary for distinctions between model predictions.

QCD at small x and forward physics

At large collision energy and relatively low momentum transfer (Q), one expects a new regime of QCD known as saturation [27]. This is described in a picture of colour glass condensate (CGC) where a saturation scale emerges naturally. This is pictorially depicted in Figure 19 in terms of the saturation domain.

One of the experimental results which support the saturation phenomenon is the lim-

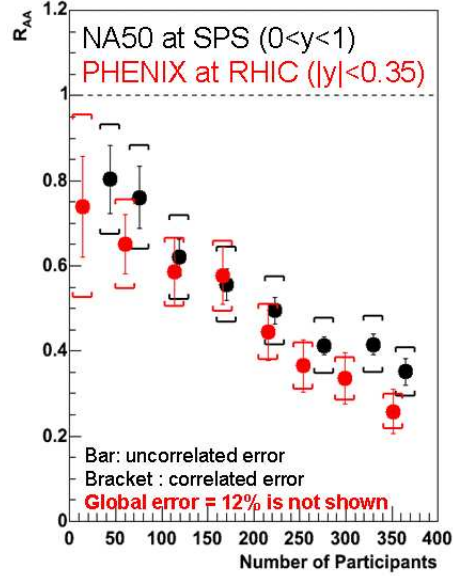


FIG. 16: Nuclear modification factor for J/Ψ for PHENIX results compared to those from NA50.

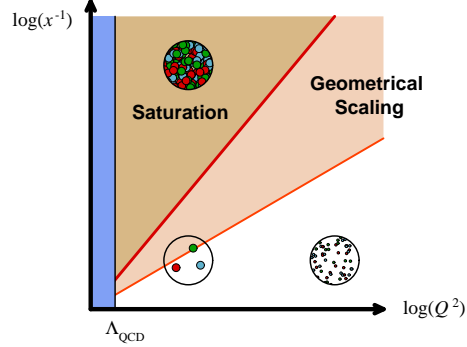


FIG. 17: Saturation domain in the (Q^2, x) plane.

iting fragmentation [28, 29], shown in Figure 18 for several beam energies and colliding systems. By shifting the rapidity axis by the beam rapidity, one can see that the rapidity distribution for produced particles at collisions of various energies and system tend to an universal curve in the fragmentation region. This property naturally follows from the CGC framework. The second observation is seen from the suppression of hadron spec-

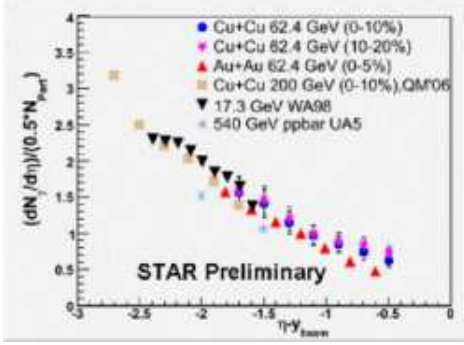


FIG. 18: Limiting fragmentation as observed from the rapidity density distribution for different collision energies and collision systems [28, 29].

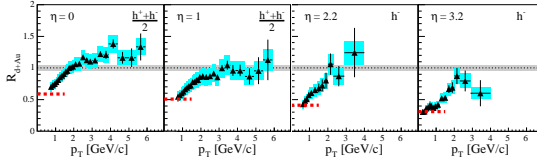


FIG. 19: Forward suppression observed by BRAHMS for d+Au collisions at RHIC [30].

tra at forward rapidity in d-Au collisions [30] from the BRAHMS experiment at RHIC as shown in Figure 19. The suppression of the nuclear modification factor at forward rapidities is considered to be a consequence of the shadowing that builds up via the evolution in rapidity.

The ALICE experiment at LHC [31, 32] will probe a continuous range of x as low as about 10^{-5} , accessing a novel regime where strong nuclear gluon shadowing is expected. The study of low x regime, especially at forward rapidities, will be most appropriate to study the early stage of nuclear collision.

Where are we now and what to expect

The field of Quark-Gluon Plasma has reached a very interesting point of its lifetime. We have the wealth of results from AGS, SPS and RHIC with us. The theoretical developments have concentrated on a complete description of the interactions of hadrons at high

energy and their subsequent evolution into a thermalized quark-gluon plasma. There has been indication of the formation of a coexisting phase of quarks and hadrons even at SPS energies [33]. The matter formed at RHIC is observed to be of low viscosity and high opacity, and is termed as strongly coupled quark-gluon plasma (sQGP). There are experimental evidences for the colour glass condensate picture which considers the high density gluonic matter. More detailed studies, with high p_T probes and high statistics data from SPS and RHIC, are being made to understand the properties of the high temperature and high dense matter. With the advent of very high energy beams at the LHC, all the three major experiments (ALICE, CMS and ATLAS) are gearing up to study the new form of matter in great detail [34].

The QCD phase boundary is slowly getting mapped with data points from various experiments. One important point which is missing from our experimental radar is the QCD critical point. We need to have a good guidance from the lattice calculations with regard to the location of the critical point. The exact location of the critical point is not known yet. A new program for the RHIC low energy scan to search for the QCD critical point is underway which will also cover a broad region of physics interest [2]. The STAR experiment is expected to take a lead in this regard. The CBM experiment [3] in the newly planned FAIR facility at GSI will be able to probe the critical point and study it in detail.

We would like to think that the field of Quark-Gluon Plasma is very much in its youth and we expect a lot of fundamental and interesting physics to happen within the next decade.

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